February 23, 1999

MEMORANDUM

SUBJECT: Williams Air Force Base (98-R09-003)

FROM: Scott G. Huling, Environmental Engineer
Technical Assistance and Technology Transfer Branch

TO: Sean Hogan, Remedial Project Manager
US EPA Region 9

An estimate of the volume of nonaqueous phase liquids (NAPL) present in the subsurface at Williams Air Force Base (WAFB) Superfund Site is provided. This estimate is intended as an independent estimate of NAPL volume for the site, for comparison to the estimates prepared by the U.S. Air Force. The calculations also provide an indirect analysis of the Air Force's various approaches for calculating NAPL volumes. A critique of the approach provided by the U.S. Air Force is also provided, in the form of discussion of pertinent issues and assumptions.

Rick Stransky and Dr. Bruce Pivetz of ManTech Environmental Technology Corporation, and Dr. Ravi Varadhan of Dynamac Corporation assisted in this review. If you have any questions or would like to discuss any of the comments and recommendations, please call at your convenience (580) 436-8610.

cc: Rich Steimle T10 (5102W)
Richard Freitas, Region IX
Herb Levine, Region IX

NAPL VOLUME ESTIMATE at WILLIAMS AIR FORCE BASE (PHOENIX, AZ) - OPERABLE UNIT 2 (ST-12 AREA)

The total LNAPL volume was calculated for the subsurface (unsaturated zone and saturated zone) at Site ST-12 at Williams Air Force Base. The site is also known as Operational Unit 2 (OU-2), and the unsaturated portion of the site has historically been known as OU-3. No analysis was made regarding the mobility or the feasibility of recovering the NAPL, however, such an analysis is currently planned. The analysis is considered preliminary since additional data and information could improve the analysis. Currently, the Air Force is preparing a comprehensive summary of additional data and information to be included in the Focused Feasibility Study Report. Assuming better data, information, and rationale were provided, the parameter values used in these calculations could be modified and the estimated range of NAPL volume re-estimated. Since the data, information, and rationale presented are currently incorporated into a spreadsheet, re-calculation could be easily conducted. Additionally, the spreadsheet could be provided to the U.S. Air Force for their use in conducting similar calculations.

Two approaches were used to estimate the volume of NAPL. These approaches were based on two different conceptual models of the source area: the continuous source zone conceptual model and the discrete source zone conceptual model. Both methods give similar results when similar layers are considered, as such, seem to support similar volume estimates. The general approach used in both procedures is summarized below.

Discrete Zones Conceptual Model: Three discontinuous (source) zones of NAPL were identified and used in the calculations. Three different layers within the shallow aquifer were used in the calculations. The volume of NAPL estimated did not include the low permeability zone (LPZ) or LPZ+1, LPZ+2, or the unsaturated zone. This approach assumed constant porosity (η=0.35), three distinct cylindrical source zones with differing thicknesses, and varying NAPL saturation.

Continuous Zone Conceptual Model: This conceptual model and the associated calculations are more complex than what is presented in the discrete source zone conceptual model. Continuous zones of NAPL were assumed to extend from the unsaturated zone down into the saturated zone and then laterally, extending from the main source area. This approach assumed varying porosity (η= 0.3 - 0.4), 8 layers, varying NAPL saturations, NAPL saturation gradients (inner core, outer core, fringe/lobe), differing thicknesses of layers, and varying saturation. Although the conceptual model assumed continuous zones of NAPL, the role of preferential pathways were considered in the analysis using the parameter, fraction of area affected ($F_{A,i}$). This factor represents the fraction of the total plan-view area which was affected by NAPL, as such it could be considered the effective cross-sectional area.

METHOD I - DISCRETE SOURCE ZONE CONCEPTUAL MODEL

Upper and lower estimates of the volume of NAPL present in the saturated zone of the upper aquifer are provided. The range in volume reported is based on a range in volumetric NAPL saturation values used in the calculations. It should be noted that this estimate does not include the NAPL present in the vadose zone or the low permeability zone (LPZ).

Summary of LNAPL Volume Estimate

The lower and upper estimates for the volume of NAPL were 940,000 and 2,810,000 gallons, respectively. Again, it should be noted that this volume only corresponds to the NAPL present in the saturated upper aquifer. Using the same general procedures, the NAPL volume present in the vadose zone (above the upper aquifer) and the LPZ could be estimated.

Basic Conceptual Framework

Three major parameters were involved in the estimation of NAPL volume, (1) the areal extent of NAPL coverage, (2) the vertical extent of NAPL penetration, and (3) the degree of NAPL saturation. NAPL volume can be generally estimated as:

$$V_T = \eta \int_X \int_Y \int_Z \ \theta(X,Y,Z)\, dX dY dZ \qquad (1)$$

where,

$\theta(X,Y,Z)$ is the spatial distribution of NAPL saturation.

The aquifer volume containing the NAPL is discretized into distinct lithologic units vertically, and distinct blocks laterally. Each of these elements can have a different NAPL saturations. Total volume is obtained by summing all the individual volumes.

$$V_T = \sum_{k=1}^{M} \sum_{j=1}^{Nk} t_{k,j}\, A_{k,j}\, \theta_{k,j}\, \eta \qquad (2)$$

where,

V_T = total NAPL volume

M = total number of source areas or sectors

N_k = total number of lithologic units in the k-th sector

$A_{k,j}$ = area of the k-th sector in the j-th lithologic unit

$t_{k,j}$ = thickness of the j-th lithologic unit in the k-th sector

$\theta_{k,j}$ = NAPL volume saturation (as a fraction of porosity) in the (k,j) element.

η = porosity of the upper aquifer

Equation 2 can also be written as follows:

$$V_T = \sum^{S} V_{T,k}\, \theta_k\, \eta\, 7.48 \qquad (3)$$

k=1

Where:

S = number of sectors (sector = one layer in one area)
$V_{T,k}$ = volume of the k-th sector
θ_k = NAPL saturation in the k-th sector
7.48 = conversion factor (gallons/ft^3)

Areal Extent of NAPL Distribution

Based on observed NAPL distributions in the monitoring wells, the site can be divided into three areas (refer to Figure 3-12 (IT Corporation, 1995c)), (1) the primary source area (A1) comprising wells W-01, W-05, W-09, W-32, W-33, LI-06, PA, PB, N-7, and DPE-1, (2) a small area around well W-11 (A2), and (3) a small area around W-13 (A3). It is assumed that wells W-11 and W-13 are not related to the primary source area. In all these wells significant free product (> 2ft) has been observed over extended periods. All the wells in the primary source area had free product levels greater than 10 ft during several sampling rounds. The areas A_1, A_2, and A_3 are assumed to be the same as that estimated by BEM (BEM, 1999b), 64,000, 9500, and 9500 ft^2, respectively. It should be noted that BEM did not consider A2, the area around W-11 in their NAPL volume calculations. Assuming these source areas were upright cylinders, the corresponding diameters would be 285', 110', and 110', respectively.

At least five distinct lithologic units can be identified at ST-12 (refer to lithologic schematics for W-01, W09, W-11, W-13, LI-06, and W-33). These units are (from top to bottom): a very coarse sand and gravel layer (layer 5), a fine-grained layer (silt + sand + clay) (layer 4), a coarse sand layer (layer 3), another fine-grained layer (layer 2), and finally another coarse sand layer (layer 1). The thickness of each layer varies somewhat between various monitoring wells. The thickness was calculated from the lithologic cross sections developed by IT. The thickness of various lithologic units underneath the three areas where significant NAPL levels have been observed is presented in Table 1.

Vertical Extent of NAPL Penetration

It is difficult to determine the vertical extent of NAPL penetration. The memorandum submitted by BEM dated May 28, 1998, estimates that the lowest water levels at the up-gradient and down-gradient edges of the primary NAPL source area (A1) are 1112 and 1110 ft MSL, respectively. These levels are below layer 3 at many of the source area wells (W-09, LI-06, and W-33) and almost at the bottom of layer 2. It is unclear what duration the water table was at these low levels and therefore, whether LNAPL reached these depths. It was reported that the NAPL was unlikely to have penetrated the fine-grained, low permeability stratum (layer 4) beneath layer 5 within the short time period in which the water dropped to this level (BEM, 1999b) does not appear substantiated given these data. The rationale for this observation has not been provided. It is probable that the water levels were below layer 5 or even layer 3 for a period sufficiently long to allow the penetration of NAPL into the layers 4 and 3. Examining the NAPL and water level time series data simultaneously, it appears that in the primary source area (Area

A1) wells

Table 1. Thickness and volume of various lithologic units in different areas of site ST-12 at Williams AFB.

Layer(1)	Primary Source Area (2) (A1) thickness (ft)	volume (ft^3)	Well W-11 (2) (A2) thickness (ft)	volume (ft^3)	Well W-13 (2) (A3) thickness (ft)	volume (ft^3)
1	11	-	8	-	3	-
2	6	-	5	-	8	-
3	5*	320,000	5	47,500	3	28,500
4	5*	320,000	6	57,000	7	66,500
5	7*	448,000	7*	66,500	9*	85,500

(1) 1 - deepest; 5 - shallowest, vertical intervals correspond to respective layers 1-5 in Table 4.
(2) A1 = 64,000 ft^2, A2 = A3 = 9500 ft^2.
- volume not calculated, * layers in which NAPL were assumed to occur.

(e.g., W-01, W-09, LI-06), there were large amounts of NAPL in the well even when the water table was at or below layer 3. This indicates a possible scenario in which free product could enter layer 3. Therefore, the smear zone or the vertical extent of NAPL penetration should include these three layers (3, 4, and 5), for the primary source area wells. In W-11 (Area A2), the free product started appearing only after the water table was in layer 5. Therefore, it is likely that the NAPL did not penetrate beyond this layer. In W-13 (Area A-3), the free product was seen in the wells when the water table was near the top of layer 4. Since prior measurements were not made, it was assumed that the vertical extent of NAPL penetration was only into layer 5.

Overall, the smear zone consists of three layers (5, 4, and 3) in the primary source area (A1), and of one layer each (layer 5) in the areas (A2, A3) surrounding W-11 and W-13. Therefore among the total fifteen sectors (3×5), we assumed only five sectors existed where significant amounts of NAPL are present, i.e. S=5 (eq 3).

Degree of NAPL Saturation

The range of NAPL saturation (θ) was assigned to each sector based on the NAPL behavior in the monitoring wells present in each sector. As discussed earlier, in the primary source area significant amounts of free product (i.e., product that is mobile as indicated by its presence in wells, and variation in the depth of NAPLs in wells) were observed during the time period in which the water table rose from below layer 3 to layer 5 and then into the LPZ. Hence, it is reasonable to assume that NAPL was present in greater than residual amounts in the layers 3, 4, and 5. The general range of residual saturation is from 15% to 40% of the pore volume (Wilson and Conrad, 1984; Mercer & Cohen, 1990; Wilson, *et al.*, 1990). Due to the mobility of NAPL observed at this site, and the corresponding NAPL saturations required for NAPL mobility, a saturation range of 30 to 90% was assumed. The corresponding volumetric NAPL saturation (mL NAPL/mL pore space) is 0.3 - 0.9. For the area around W-11, it was assumed that the NAPL saturation range was also 0.3 to 0.9 in layer 5. In W-13, the product was observed only when the water table was just below layer 5, and it disappeared (smeared) as the water table rose into layer 5. Therefore, it was assumed that the volumetric NAPL saturation was 0.15 to 0.4 for layer 5 in this sector. The NAPL saturation values for each lithologic unit in each discrete area is reported in Table 2.

Table 2 - NAPL saturation ranges for lithologic units in the Discrete Conceptual Model.

Layer	NAPL saturation (mL/mL)		
	Area A1	Area A2	Area A3
3	0.3 - 0.9	0	0
4	0.3 - 0.9	0	0
5	0.3 - 0.9	0.3 - 0.9	0.15 - 0.40

In conjunction with the estimated aquifer volumes for each sector (Table 1), the NAPL saturation ranges (Table 2), and assuming a porosity (η) of 0.35, the volume of NAPL in the area of ST-12 was estimated using eq 3 (Table 3). The lower and upper estimates for the volume of NAPL were 940,000 and 2,810,000 gallons, respectively. It should be noted that this volume only corresponds to the NAPL present in the saturated upper aquifer. Using the same general procedures, an additional volume could be calculated to account for the NAPL present in the vadose zone above the upper aquifer.

Table 3 - The estimated volume of NAPL for each lithologic unit.

Layer	Volume NAPL (gallons) [1,2]		
	Area A1	Area A2	Area A3
3	250,000 - 750,000	0	0
4	250,000 - 750,000	0	0
5	350,000- 1,055,000	52,000 - 156,000	34,000 - 89,000

(1) The range of NAPL volume reported is based on the range of NAPL saturations reported in Table 2.
(2) Cumulative total = 940,000 - 2,810,000 gallons NAPL

METHOD II - CONTINUOUS SOURCE CONCEPTUAL MODEL

Summary of LNAPL Volume Estimate

The total LNAPL volume was calculated for the subsurface (unsaturated zone and saturated zone) at Site ST-12 at Williams Air Force Base. The horizontal and vertical extent of

LNAPL-affected areas were delineated. Parameter values for LNAPL saturation, geologic unit porosity, and fraction of subsurface affected by LNAPL are developed and reported. Ground-water elevation data, LNAPL thickness information, lithologic information, and results from soil sampling and analysis were used in this evaluation.

Estimates for total LNAPL present in the unsaturated and saturated zones of Site ST-12 range from 3,500,000 to 11,000,000 gallons. The range in the unsaturated zone is 2,700,000 to 7,000,000 gallons. This is concentrated in a relatively smaller area for the first 130 feet below ground, which then broadens from 130 feet down to the water table at 175 feet below ground. NAPL is generally assumed to be at residual saturation, and heterogeneously distributed throughout the soil. The total volume of NAPL estimated in the saturated zone ranged between 780,000 to 3,800,000 gallons.

Detailed discussion regarding the calculations, data, and logic used to arrive at these estimated volumes are provided below. This analysis is preliminary, as it is anticipated that more data will become available to refine this analysis.

Data Sources

Calculations associated with the unsaturated zone were based primarily on the soil data contained in the OU-3 Remedial Investigation (IT Corporation, 1994), in combination with the Phase II Stage 2 Report (AeroEnvironment, 1987b). Calculations associated with the saturated and free product zone were based on LNAPL monitoring data compiled from various sources, but primarily the TS/RAD Report (IT Corp, 1998). This data was complemented by water level data included in the spreadsheet prepared by IT and submitted via e-mail to USEPA in 1998.

Table 4 - Description and vertical intervals of lithologic units.

	Description	Vertical Interval (ft bls)	(ft msl)
Unsaturated zone Upper		25-130	1305-1200
Lower		130-175	1200-1155
Saturated zone LPZ+2		175-178	1152-1155
LPZ+1		178-185	1145-1152
LPZ (low permeability zone)		185-200	1130-1145
Shallow Aquifer Unit 5	coarse-grained layer, sand and gravel	200-208	1122-1130
Unit 4	fine-grained layer, sand-silt-clay mixture	208-214	1116-1122
Unit 3	coarse-grained layer, predominantly sand	214-220	1110-1116
Unit 2	fine-grained layer, sand-silt-clay mixture	220-225	1105-1110
Unit 1	coarse-grained layer, predominantly sand	225-232	1097-1105

Aquitard	clay	>232	< 1097

It should be noted that due to the length of the activities at the site, which were initiated in the 1980s, the data have not been compiled in any organized manner in any single location prior to this analysis. During this evaluation, it was evident that the available data and information was incomplete and contained apparent errors and inconsistencies. This is not surprising due to the length and breadth of the studies conducted at this site. Due to time constraints, other data which are presumably available were not used to any great extent. These data include dissolved concentration data from the saturated zone, PID or FID screening data of soil or water samples, visual and olfactory notes included on field logs, site-specific aquifer properties data, geophysical data, LNAPL recovery information and testing, and LNAPL analytical data. If accurate and completely compiled, these data could improve the accuracy of the estimates provided in this report.

Approach

The parameters required to calculate LNAPL volume in the subsurface include the following:

1. The horizontal and vertical distances in which the LNAPL is distributed (feet);

2. LNAPL saturation values (in percent of the pore space occupied by LNAPL, and in bulk percent of the unit);

3. Porosity (unitless); and

4. Fraction of geologic unit volume affected by the LNAPL (in percent)

The information and analysis used to establish each of these parameters are discussed in detail below. Either a single value or a range of values was selected for each of these parameters. The calculations were completed using a spreadsheet.

Geology

The geologic cross-sections prepared by the conceptual site model subcommittee were utilized. To ease discussion of the various lithologic units in this analysis, the units were designated as indicated in Table 4. The shallow aquifer units (layers) 1-5 correspond to the same layers 1-5, respectively in the discrete source zone conceptual model. Elevations and thicknesses of each of the Shallow Aquifer units were measured for each of the wells using these cross-sections. The thicknesses and elevations of each unit showed variation from well to well. A site-wide dip to the southwest for the stratigraphic units has been suggested by an Arizona state hydrologist (Mr. Don Atkinson).

Volume of LNAPL

The total volume (V_T) of LNAPL present at the site was calculated as follows:

$$V_T = \Sigma^n{}_{i=1} (A_i \times h_i \times F_{Ai} \times S_i \times \eta_i \times 7.48) \qquad (4)$$

where,

V_T sum of LNAPL volumes, in gallons (for all vertical zones)

A_i plan view area of NAPL source (ft^2) based on ellipse or triangle shapes
ellipse shape = ($\pi \times \frac{1}{2} L \times \frac{1}{2} W$)
triangle = $\frac{1}{2} \times$ base $\times$ height (285,000 ft^2 for the fringe/lobe area)

h_i height of the lithologic unit, in feet

S_i LNAPL saturation (both volumetric and total volume methods were provided in the spreadsheet for illustrative purposes only)
volumetric NAPL saturation = volume of NAPL (mL)/volume of void space(mL)
total volume NAPL saturation = volume of NAPL (mL)/total volume of porous media (mL), eq 4 is modified to exclude η_i when using this parameter

F_{Ai} fraction of the total volume containing NAPL $\times$ 100 (%)

η porosity (unitless)

7.48 conversion factor (gal/ft^3)

Assumptions

The following assumptions were used to simplify the NAPL volume estimation procedures. Other assumptions have also been made for simplification procedures and are discussed in the text in following sections.

1. LNAPL that appears in a well is mobile LNAPL. Fluctuations in LNAPL thickness within a well clearly indicate that the LNAPL is moving into and out of the subsurface. This warranted using higher values of NAPL saturation in the calculations.

2. LNAPL presence in a well indicates the presence of mobile LNAPL in the aquifer (near the well).

3. LNAPL thickness in a well is qualitatively related to the LNAPL saturation value in the aquifer. Wells with frequent high thicknesses of LNAPL are in areas of greater LNAPL saturation than wells with low thicknesses or infrequent occurrences of LNAPL.

4. The presence of LNAPL in a well at a certain ground water elevation indicates that LNAPL was present in the aquifer at that elevation, if the screen is present at that elevation.

5. LNAPL will take some period of time to enter a well after initial installation of the well.

Horizontal and vertical extent of NAPL

The horizontal and vertical extent of LNAPL were delineated using the following evidence:

1. The presence of LNAPL in a well, identification of all wells with LNAPL, relative thickness of LNAPL, and identification of the date(s) and ground-water elevation(s) at which LNAPL occurred in a well.

2. Location of potential or known source areas.

3. Contaminant presence in soil samples from soil and well borings.

4. Ground water quality analytical data.

At a minimum, each well that has historically contained floating LNAPL is considered in the analysis. Such wells were identified using site reports and data. This information was arranged so that the water table elevations on certain dates could be correlated with the date of LNAPL thickness measurements. For example,

Well LI-06	Date	Water Elevation	LNAPL Thickness
	Jan-91	1121.76	9.10
	Nov-90	1121.06	10.62
	Oct-90	1120.25	9.66

These tables of arranged data have not been included with this report. Based on this approach, it was noted that data gaps exist where no water elevation data are available, or a definitive indication of LNAPL thickness is not provided. In a few instances, water table elevations were interpolated from nearby wells, assuming a linear trend in ground water elevations between those wells. If LNAPL thickness was not reported, it was unclear whether this indicated that no LNAPL was present during a measurement or if no measurement was made.

This analysis allowed an estimation of when, at what water table elevation, and in what unit LNAPL was present. Table 5 is a summary of information regarding LNAPL appearance in wells at the site. It should be noted that the water elevation and unit at which LNAPL was first noticed does not necessarily indicate the lower boundary of the LNAPL zone. This is because the water elevation and unit are dependent on when the well was installed. For example, in W-05, LNAPL appeared at 1118 ft msl at the time the well was installed. LNAPL might have occurred in the well at a lower elevation had the well been constructed earlier when the water elevation was lower.

Examination of the presence of LNAPL in individual wells provides information on which to determine the horizontal and vertical extent of LNAPL. These observations and related discussion have been summarized in Table 6.

Table 5 - LNAPL appearance summary.

Generalized LNAPL history	Well	Date installed	Date LNAPL appeared	Water elevation (ft msl) when LNAPL was first noticed	Piezometric surface was in this unit when LNAPL was first recorded
Wells generally with greater thicknesses of LNAPL	W-01	8/89	<9/89	<1118.74	4
	W-05	10/89	10/89	<1118.43	3
	W-09	10/89	10/89	<1118.01	3
	W-32	3/94	<8/94	~1131-1135	LPZ
	W-33	3/94	<8/94	~1130-1134	LPZ
	PA	10/93	<7/96	>~1140	LPZ
	N-6	9/96	9/96	~1139-1142	LPZ
	N-7	9/96	9/96	~1139-1142	LPZ
	DPE-1	9/96	9/96	~1139-1142	LPZ
Wells in which LNAPL appeared after an initial period of no LNAPL	W-03	8/89	<12/96	1138-1141 (1126) [1]	LPZ [2] (5) [3]
	W-08	10/89	<9/97	1139-1141 (1129) [1]	LPZ[2] (5) [3]
	W-11	11/89	7/94-2/95	>1124.46	5
Wells in which LNAPL disappeared	LI-06	3/87	<7/89	<1118.76	4
	W-13	10/89	<11/89	<1120.93	4
Wells with fewer occurrences of LNAPL, thinner layers, or shorter periods of time.	W-04	8/89	12/96	1138-1141 (1127) [1]	LPZ [2] (5) [3]
	W-18	7/90	2/91	1125.24	5
	PB	10/93	<9/96	~1139-1142	5/LPZ
	N-13	12/97	<9/98	>1146	LPZ/L1

(1) This elevation is the elevation of the top of the screen.
(2) This well was not screened in the LPZ: the screen ended in unit 5.
(3) Unit in which the screen top is found.

Table 6. LNAPL in individual wells.	
Wells generally with greater thicknesses of LNAPL	
W-01	Significant thicknesses of LNAPL have been present throughout the lifetime of this well, with lesser thicknesses occurring during LNAPL recovery activities
W-05	Significant thicknesses of LNAPL have been present throughout the lifetime of this well; this implies that a LNAPL boundary could be some distance to the south of this well. It should be noted that the next well (W-06) in the south direction is approximately 350' away.
W-09	Significant thicknesses of LNAPL have been present throughout the lifetime of this well, with lesser thicknesses occurring during LNAPL recovery activities; this implies that a LNAPL boundary could be some distance to the south/southwest of this well.
W-32	When the well was installed, the water elevation was in the LPZ (where the top of the screen was). The first measurement after well installation (and equilibration) indicates that LNAPL was present. There are insufficient data to make definite conclusions, but it appears likely that LNAPL could be present in Unit 5.
W-33	When the well was installed, the water elevation was just below the Unit 5/LPZ boundary (the top of the screen was in the LPZ). The first measurement after well installation (and equilibration) indicates that LNAPL was present. There are insufficient data to make definite conclusions, but it appears likely that LNAPL could be present in Unit 5.
PA	When the well was installed, the water elevation was at the Unit 5/LPZ boundary (the top of the screen was in the LPZ). There are insufficient data to make definite conclusions, but it appears likely that LNAPL could be present in Unit 5, because this well is near W-05, in which LNAPL definitely was found in Unit 5.
N-6	This well was installed when the water table elevations were in the LPZ. Although this well is screened throughout the Shallow Aquifer, the LPZ, and overlying units, it is likely that LNAPL in this well is from Unit 5, at least partly, due to the proximity to wells where it is known that LNAPL is in Unit 5.
N-7	This well was installed when the water table elevations were in the LPZ. Although this well is screened throughout the Shallow Aquifer, the LPZ, and overlying units, it is likely that LNAPL in this well is from Unit 5, at least partly, due to the proximity to wells where it is known that LNAPL is in Unit 5.
DPE-1	This well was installed when the water table elevations were in the LPZ. Although this well is screened throughout the Shallow Aquifer, the LPZ, and overlying units, it is likely that LNAPL in this well is from Unit 5, at least partly, due to the proximity to wells where it is known that LNAPL is in Unit 5.

Table 6. Continued	
Wells in which LNAPL appeared after an initial period of no LNAPL	
W-03	No LNAPL had previously appeared, but 3-1/2 years after the screen had been submerged, LNAPL appeared. Since it is assumed that LNAPL must enter the well through the screen, this indicates that LNAPL became present somewhere in the vertical interval of the screen (1086 to 1126 ft MSL). This LNAPL must be due to mobilization of LNAPL in Unit 5, or downgradient migration of LNAPL into the region of W-03. This occurred as the piezometric level increased, but not quite to the LPZ/LPZ+1 boundary.
W-08	No LNAPL had previously appeared, but 3-1/2 to 4 years after the screen had been submerged, LNAPL appeared. Since it is assumed that LNAPL must enter the well through the screen, this indicates that LNAPL became present somewhere in the vertical interval of the screen (1089 to 1129 ft MSL). This LNAPL must be due to mobilization of LNAPL in Unit 5, or downgradient migration of LNAPL into the region of W-08. This occurred as the piezometric level increased, but not quite at the LPZ/LPZ+1 boundary.
W-11	LNAPL had appeared when the water level was at about the midpoint of Unit 5. This LNAPL must be due to mobilization of LNAPL in Unit 5, or cross-gradient migration of LNAPL into region of W-11. LNAPL decreased, then increased as the piezometric level increased, but not quite at the LPZ/LPZ+1 boundary.
Wells in which LNAPL disappeared	
LI-06	Screen submergence can explain the disappearance of LNAPL in this well.
W-13	LNAPL appeared in the well soon after installation (less than one month). LNAPL has presumably all become immobilized.
Wells with fewer occurrences of LNAPL, thinner layers, or shorter period of times	
W-04	No LNAPL had previously appeared, but 3-1/4 years after the screen had been submerged, minor LNAPL appeared. Since it is assumed that LNAPL must enter the well through the screen, this indicates that LNAPL became present somewhere in the vertical interval of the screen (1087 to 1127 ft MSL). This LNAPL must be due to mobilization of LNAPL in Unit 5, or downgradient migration of LNAPL into the region of W-04. This occurred as the piezometric level increased, but not quite at the LPZ/LPZ+1 boundary.
W-18	LNAPL possibly disappeared prior to screen submergence, and thus has presumably all become immobilized. Alternatively, screen submergence could explain the disappearance.
PB	**Table 6. Continued** When the well was installed, the water elevation was just below the Unit 5/LPZ boundary (the top of the screen was in the LPZ). There are insufficient data to make definite conclusions, but it appears likely that LNAPL could be present in Unit 5 because the top of the well screen is at the Unit 5/LPZ boundary. This well is interesting because although it is near W-05, it has had much less LNAPL than W-05. The bottom of the PB well screen is at a higher elevation (1112.4 ft MSL in Unit 2) than that of W-05 (1090.3 ft MSL in the aquitard), or most other wells. This raises the possibility that the high levels of LNAPL found in those other wells might in fact be coming from elevations below the PB well screen (i.e, below 1112.4 ft MSL, in Unit 1). This well is interesting also because it appears that LNAPL did not occur for about the first 10 feet of water elevation rise. This should be confirmed as being from actual confirmed non-detects rather than from merely a data gap.
N-13	There is only one data point for this well, so little can be inferred, other than that LNAPL is present.

The information contained in Tables 5 and 6 was used to delineate the horizontal and vertical extent of LNAPL-affected portions of the subsurface. This delineation is discussed in the Results section, below, by geologic unit and by portion of the site.

LNAPL Saturation Values

As NAPL flows through porous media, a portion of the NAPL remains in the porous media as a residual. NAPL saturation value ranges identified in Cohen and Mercer (1993) were used as the basis for NAPL saturation values used in these calculations. Residual saturation values in the unsaturated zone typically range from 0.1 to 0.2, while values in the saturated zone typically range from 0.1 to 0.5. When free product is present in a well, the saturation value will exceed the residual saturation, and the value could range up to 0.9 (Schwille, 1988; Weaver, 1999). The selection of specific S_i values are described below in the discussion of geologic units and regions of the site.

An inner core area is defined as the area of relatively greatest contamination, and extends deepest beneath the site. The degree of contamination (i.e., S_i) decreases with distance from the inner core. An outer core surrounds the inner core, and has relatively less contamination. Surrounding the outer core is a fringe/lobe area, which has the least contamination.

The range of values used to represent residual saturation (0.1 to 0.2) has been used for the entire unsaturated zone. This range is also used for the recently saturated layers, LPZ and LPZ+2, because these layers were unsaturated until recently, and have been only recently impacted by any LNAPL rising on the rising water table. It is assumed that NAPL migration into LPZ+2 is time dependent and S_i, assumed to be presently low, will increase with time. This low range also reflects the possibility that these units are still unsaturated (i.e., if the water elevation measurements actually indicate a piezometric surface of Unit 5 rather than an actual water table). A slightly greater saturation value range (0.1 to 0.4) is used for the coarser LPZ+1 unit because of the potential for greater LNAPL movement through this coarser unit.

The area around the wells having the greatest thicknesses of LNAPL (e.g., W-01, W-05, W-09, N-6, N-7, DPE-1, LI-06) was designated as the ‘inner core’. Due to the relatively great LNAPL thicknesses and the potential of this area being the ‘source area’, the highest LNAPL saturation values were used within this inner core. A saturation value range of 0.4 to 0.9 was used for Unit 5 because of the frequent occurrence of thick LNAPL layers when the water elevation was in Unit 5. The high end estimate of 0.9 is supported by Schwille (1988) and Weaver (1999). A large saturation value range (0.1 to 0.7) was used for Units 3 and 4 within the inner core because of the uncertainty associated with the occurrence and duration of the water table below this level, and therefore the level of contamination.

Surrounding the inner core is an area having wells that have had relatively large thicknesses of LNAPL (e.g., W-32, W-33, W-03, W-08, PA) while the water elevations were in Unit 5, but not to the degree of the inner core. This area is designated the ‘outer core’ and is given a lower LNAPL saturation range of 0.2 to 0.4, relative to the inner core. This range reflects the confirmed presence of LNAPL (mobile LNAPL), and also a probable decrease in the amount of LNAPL with increasing distance away from the source area (inner core). The area around W-11 is also considered part of the outer core (although possibly not connected to it), with a saturation value range of 0.2 to 0.4, because of the relatively recent detections of significant thicknesses of LNAPL in this well.

Surrounding the outer core is an area where LNAPL has been detected in wells (e.g., W-18, W-13, W-04, N-13), but not to the degree as in the inner or outer cores. This area, occurring within Unit 5, is designated as the 'fringe/lobe' area. A lower range of saturation values (0.1 to 0.2) is used, which reflects the increasing distance away from the most significant areas of LNAPL.

In conjunction with the rationale for NAPL saturation values and individual but continuous aquifer units in the source areas, the values of NAPL saturation (volumetric and total) are presented in Table 7.

Porosity

Consistent with the approach and the general values used in Fetter (1980), and in general, consistent with values identified in various reports for the site, a porosity value of 30% was selected for coarse sand and gravel zones (cobble zone or gravel zones), 35% for moderate or fine sand zones (coarse zones) and 40% for silt or clay zones (fine zones). These values are reported for each source zone area (Table 7).

Fraction of aquifer volume affected

It was assumed that as LNAPL migrates vertically through the soil profile it may develop preferential flow paths leaving behind certain areas more contaminated (greater S_i) than others. To compensate for this potential occurrence in the NAPL volume estimate, the fraction of aquifer volume affected (F_{Ai}) was assumed and used in the NAPL volume calculation. Different values were selected for various zones to account for preferential pathways. One possible conceptualization of this heterogeneous effect, is that the finer-grained units will be more affected than coarser-grained units simply due to lower permeability. This is reflected in Table 7 by units LPZ+2, LPZ and Layer 4 which are represented using ranges of 0.2-0.9, 0.2-0.9 and 0.7-0.9 for F_{Ai}, respectively. The lower range in values for LPZ+2 is attributed to the rising water table in this unit. Some areas may not yet be completely saturated.

Based on the rising water table (and LNAPL), it is assumed that the preferential mode of NAPL spread will be minimized and the area affected would be more uniform than the unsaturated zone.

RESULTS

The horizontal extent of the LNAPL-affected areas in the unsaturated zone is presented in Figure 1. The horizontal extent for two vertical zones (25 to130 ft bgs and 130 to 175 ft bgs) are delineated. The horizontal extent of the LNAPL-affected areas in the saturated zone is indicated in Figure 2. Three areas have been designated on this figure. The inner core is the area of relatively greatest contamination, the outer core has relatively moderate contamination, and the fringe/lobe area has the relatively least contamination. Figure 3 is a conceptual sketch of the cross-sectional distribution of contamination at the site.

It should be noted, there is not a unique solution to the contouring of NAPL presence in the unsaturated or saturated zones. The plan-view areas represented in Figures 1 and 2 could be drawn differently which would result in different estimated values for NAPL. For example, there are locations in the study area where the next closest well or soil sampling location that would be used to identify a boundary is located a large distance away. One approach would be to assume the boundary is half-way between two such data points, Assuming this approach, the plan-view areas would be significantly greater in some areas of the study area than what has been presented in the current figures. Correspondingly, the projected NAPL estimate would also increase significantly.

The areas of the elliptically-shaped inner and outer cores, as indicated on Figures 1 and 2, were calculated using the dimensions given in Table 4. These dimensions, the width and length of the elliptical area, were each divided by 2, multiplied together, and then multiplied by π (i.e., the formula for the area of an ellipse). The area of the inner core was subtracted from the area of the outer core, which surrounds it, to provide the area of the outer core alone. The fringe/lobe region was divided into triangular-shaped regions. The areas of these regions were summed, and the area of the outer core subtracted from the sum, to provide the total area of the fringe/lobe region.

Unsaturated Zone

It was assumed that the top 25 feet of the soil zone was excavated and therefore, not included in the NAPL volume estimate. However, verification of this assumption was not possible since the details associated with this activity were not included in the information available during this review. The soil data used are from the OU-3 RI (IT, 1993), in combination with the Phase II Stage 2 Report (AeroEnvironment, 1988). An additional set of data from 5 borings that was noted in the OU-2 RI (IT Corporation, 1994) was not included due to an inability to locate the data. Samples represented in the data set had been analyzed for total recoverable petroleum hydrocarbons (TRPH) by EPA methods 418.1 or modified method 8015 for TRPH as jet fuel. Calculations are based on detections greater than 100 milligrams per kilogram (mg/kg) dry weight, which was the local regulatory value noted in the reports (IT, 1993; AeroEnvironment, 1987b). The unsaturated zone was subdivided into two zones, the upper and the lower. The rationale for this separation is provided below.

Site specific saturation values were not provided in any of the documents provided. Based on the soil contamination data, no correlation was established between TPH and S_i. Therefore, a range of probable values was used for the unsaturated zone based on literature reported values (0.1 - 0.2). The corresponding total saturation values based on bulk values are 0.04 to 0.07 (also included in the spreadsheet). In addition, it is expected that preferential flow paths would develop as LNAPL flows through the unsaturated zone. While this is not readily apparent in the data, some preferential flow is inferred, and is expected to be present to some degree and a percent of the aquifer affected was given a range of from 70% to 90%.

Upper Unsaturated Zone

Vertical Delineation. The top zone is from 25 feet bls (1305' msl) to 130 feet bls (1200' msl). The top zone contains two separate plumes associated respectively by source borings SB-4 and SB-6 (western plume, commonly referenced as *Area 3* or the *former tank 538 area including the fuel distribution line running southward from the tank area*) and source boring SB-7 (eastern plume, commonly referred to as *Area 4* or *facility 548*). Only these borings have detections in the upper zones that have a relation to the LNAPL detected in any wells otherwise discussed in this analysis.

Lateral Delineation. The data indicates two near-surface high concentration areas (east and west). In addition, there were a number of other detections connected to each of the areas (as described by AeroEnvironment, 1987b) indicating that perhaps each of these plumes is an agglomeration of a number of release events. In addition, other release events were detected at ST-12, but none were noted to have affected the water. The western plume, concentrated around borings SB-4 and SB-6, is laterally defined by three borings, clockwise from the east, borings SB-10, SB-5 and SB-11. The eastern plume (concentrated around source boring SB-7) is laterally defined by four borings, clockwise from the north by borings SB-14, SB-9, SB-8 and SB-10.

Lower Unsaturated Zone

Vertical and Lateral Delineation. The lower unsaturated zone is from approximately 130' bls (1200' msl) to 175' bls (1155' msl). The 130 feet bls depth is within the cobble zone, which itself lies upon a thick fine grained unit. Data from source areas SB-7 (eastern plume) and SB-4 (western plume) indicate that LNAPL flowed vertically downward until, at approximately 130 feet bls (1200' msl), in the coarse-grained 'cobble zone,' the LNAPL becomes more laterally distributed. Lateral movement is indicated by data from boring locations SB-08 and SB-09b: TRPH detections, which are below 10 mg/kg above 130 feet bls (1200' msl), increase to levels greater than 1,000 mg/kg at 130 feet bls (1200' msl).

In all lithologic layers at and below the 'cobble zone,' in the lower zone, the plume extends outward, presumably in all directions relative to the upper plume. As noted by the ADEQ hydrologist (Mr. Don Atkinson) migration may be to a greater degree to the west or southwest consistent with regional dip of the layers, but no data appear to exist to confirm such a trend at this interval. The two plumes nearly join based on intermediate detections in boring SB-10 in the range of 10 mg/kg.

Saturated Zone

The saturated zone is divided into the LNAPL affected portion of the site above the Shallow Aquifer (the entire area is considered affected and is referred to on the spreadsheet as LPZ+) and the contaminated portion of the Shallow Aquifer (layers 3-5). Both zones appear to have their center of mass to the south and west of the uppermost source zones in the unsaturated zone. In addition, each of the two zones are identically divided into an inner core and an outer core, with a fringe/lobe in layer 5. Saturation values increase from the fringe/lobe towards the inner core.

Inner Core. The inner core is defined by the wells within it which contain LNAPL, including wells LI-06, W-01, W-05, W-09, PB, DPE-1, N-6, and N-7. The LNAPL thickness trends of these wells indicate that the LNAPL appears to be related to lithologic units 3, 4 and 5 (the upper 3 units of the Shallow Aquifer). Saturation values in this area are the highest of the three areas.

Outer Core. The outer core is defined by the wells within it which contain LNAPL, including wells W-03, W-08, W-11, W-32, W-33, and PA. The LNAPL thickness trends of these wells indicate that the LNAPL appears to be related to lithologic unit 5 of the Shallow Aquifer. Saturation values in this area are intermediate.

Fringe/lobes. The fringe/lobe is defined by the wells within it which contain LNAPL, including wells W-04, W-13, N-13, and W-18. The LNAPL thickness trends identified for these wells indicate that the LNAPL appears to be related to lithologic unit 5 of the Shallow Aquifer. LNAPL saturation values in this area are the lowest of all areas.

LPZ+

Vertical Delineation. This portion of the NAPL source is delineated at the approximate 175 foot bls (1155 MSL) interval as noted in borings SB-10 and SB-05 and extends to 200 feet bls (1130 feet MSL). This interval is related to the second phase of lateral migration and coincides with the current water table elevation. The lateral migration appears to occur in the coarse grained unit above the LPZ.

Lateral Delineation. This zone is similar in location, size and shape to the lower unsaturated zone except.

Shallow Aquifer

Unit 5

Vertical Delineation. The NAPL area is delineated by a distinct feature of lateral NAPL migration. This feature is evident at the approximate 200 feet bls (1130 feet MSL) interval and extending through the depth of unit 5 to 210 feet bls (1120 MSL). Delineation is marked by free product detection in monitoring well W-11. Free product appears in this well only after the water level rises into the uppermost coarse unit (layer 5) in the Shallow Aquifer. It is surmised that free product may have appeared sooner than the data indicate. Review of water levels in well W-11 from March 1995 through February 1995 (when LNAPL is detected) indicates that the water levels over this interval drops 2 feet, while site-wide water levels rise by 3 or more feet. This is interpreted to indicate that water levels may have been depressed by LNAPL, but that the LNAPL may have gone undetected.

Lateral Delineation. The inner core is generally similar in location, size, and shape to the upper NAPL areas except there are lateral extensions of the NAPL area. For example, it has an outer core to the southwest as indicated by detections in well W-11. It is presumed that NAPL transport may have occurred in this direction (towards W-11 from the northeast to the southwest) due to the slope of the floor of unit 5 or simply through a random connection of preferential pathways. It is unclear whether these NAPL areas are connected or whether these represent releases from different sources.

Unit 5 has a fringe/lobe associated with the outer core in the southwest as describe above. It also extends to the northwest as indicated by detections in borings SB-01 and SB-03 as well as LNAPL in W-18; and perhaps to the northeast as indicated by LNAPL in well W-04. Due to insufficient data, the calculations do not include the possible fringe/lobe extension to the northeast.

Units 3 - 4

Vertical Delineation. Information in Tables 5 and 6 indicates that contamination was deepest in the inner core portion of the site, likely reaching units 3 and 4.

Lateral Delineation. This zone is similar in location, shape and size to the Unit 5 NAPL inner core area. It does not have an outer core.

Calculations

The LNAPL volume is calculated for each layer using eq 4. The volumes are summed to obtain an estimate of the cumulative volume (Table 4).

Assuming the areas affected by NAPL was not compensated for preferential pathways, the fraction of aquifer volume affected (F_{Ai}) would be 1.00 in all cases. This calculation was performed and the values for minimum and maximum volume of NAPL would be multiplied by factors 1.7 and 1.2, respectively. Essentially, this indicates that the estimated range of NAPL volume could be greater than estimated (as indicated in Table 7).

Discussion

Based on the information and analysis above, estimates for total LNAPL present in the unsaturated and saturated zones of Site ST-12 range from 3,500,000 to 11,100,000 gallons. The upper and lower NAPL volume estimates for the unsaturated and saturated zones are 2,700,000 - 7,000,000 and 780,000 - 3,800,000 gallons, respectively. The upper NAPL volume estimate in the unsaturated zone represents approximately 64% of the upper total estimate. This is concentrated in a relatively smaller area for the first 130 feet below ground, which then broadens to a relatively larger area from 130 feet down to the water table at 175 feet below ground.

Despite the low NAPL saturation values used, the relatively large NAPL fraction in the unsaturated zone is primarily attributed to the significant depth over which it is distributed. The uppermost unit in the Shallow Aquifer (i.e. Unit 5) has the relatively greatest amount of LNAPL. Further, the bulk of the NAPL (70-84%, lower and upper estimates, respectively) is contained in the inner core of the NAPL source areas as depicted in Figures 1 and 2.

Comparison between the discrete zone and continuous zone conceptual models yielded generally similar results for layers 3, 4 and 5, despite significant differences in parameter values used in the calculations. For example, although the volume of media was much greater in the continuous zone conceptual model, the area affected (F_{ai}) and S_i were offset to account for heterogeneities such as preferential pathways and NAPL distribution.

It was assumed that the bulk of the contaminants, as represented by benzene, toluene, ethyl benzene, and xylenes (BTEX) were present in the NAPL phase. An analysis of the phase distribution of these compounds between the NAPL, aqueous and solid (sorbed) phases indicated that approximately 99.6% of the BTEX was present in the NAPL (refer to Attachment 1 - BTEX Phase Distribution). Therefore, the primary focus of mass distribution was based on the LNAPL.

The range of NAPL volume values presented here are clearly greater than the most recent range (upper and lower estimate) provided by the consultants for the U.S. Air Force (84,000 - 691,000 gallons, 1/19/99 fax from BEM via Sean Hogan (BEM, 1999b).

Recommendations

1. This analysis is preliminary, and although it included a large amount of data and information, there is a larger set of data to be examined. In addition, the accuracy of some of the data used should be reviewed. Additional types of data that could be examined for additional insight to LNAPL presence and saturation values (i.e., quantitation) include:

a. PID readings from soil and well borings

b. Visual and olfactory indications from soil and well borings

c. Dissolved contaminant concentrations in water samples.

d. Correlation of water level changes and stratigraphy with LNAPL thickness measurements and dissolved contamination concentrations.

2. An accurate and complete compilation of water level measurements and LNAPL thickness measurements for all measurement periods is necessary. It is recommended that the tabulated data include the following:

Date
Is LNAPL present? (Y/N)

How did you confirm that no LNAPL was present?
Water table elevation (if no LNAPL is present)
LNAPL thickness (if present)
Water/LNAPL interface elevation
Water table elevation (corrected for LNAPL thickness)
LNAPL recovery activities

3. Accurate and complete information on LNAPL measurements in soil should be compiled.

4. Accurate and complete information on LNAPL recovery volumes, and where the recovery occurred, should be compiled.

5. It is recommended to sample piezometers PC-D, PD-D, and/or PE-D (which have screen intervals about 1109 to 1116 ft MSL) to see if LNAPL is present at those elevations (i.e., in layer 3).

6. The scientific basis on which to extrapolate (back in time) the water table elevations is unclear. A more extensive and supportable analysis of the water table elevation history (i.e., lowest possible water table during the period (1941-1993) of potential LNAPL releases) is recommended.

COMMENTS REGARDING THE LNAPL VOLUME ESTIMATION BY THE AIR FORCE

I. Summary of Air Force (BEM 1999a; 1999b) LNAPL Volume Estimates

Volume of Affected Aquifer (ft^3)		NAPL Volume (gal)		Information
Minimum	Maximum	Minimum	Maximum	Source
952,000	2,652,000	427,257	1,190,217	(1)
1,457,000	3,207,000	654,000	1,439,000	(2)
374,000	1,540,000	84,000	691,000	(3)

Information Sources:

(1) 6/10/98 memo from BEM: "The Estimation of the Volume of NAPL in Site ST-12" (BEM, 1998).

(2) 1/8/99 fax from BEM via Sean Hogan: "Horizontal Distribution and Volume estimation of Free Product" (BEM, 1999a).

(3) 1/19/99 fax from BEM via Sean Hogan: "Revised estimation of NAPL volume at site ST-12" (BEM, 1999b).

II. Discussion. The comments below discuss assumptions or approaches used by the Air Force in their LNAPL volume estimates, and address some written comments from Patrick Haas. The comments are grouped by general subject matter.

Horizontal Delineation

(1) Well Data Utilized. The wells used to delineate horizontal areas affected by LNAPL in the LNAPL estimates by BEM (BEM, 1999b)are as follows:

Smallest volume estimate:	W01, W05, W09, LI06
Medium volume estimate:	W01, W05, W09, LI06, W32, W33
Largest volume estimate:	W01, W05, W09, LI06, W32, W33, W13

Wells W03, W08, W11, W18, and PA also need to be considered because they have contained LNAPL. Wells N-6, N-7, and DPE-1 also have had floating LNAPL but they are in the area already considered in the smallest BEM estimate (BEM, 1999b).

(2) Lateral Extent of LNAPL Residual Saturation. The plumes presented in prior discussions do not include all wells within which LNAPL has been detected, nor does the explanation associated with the plumes aid in integrating all of the LNAPL monitoring data. Plume boundaries should match the site conceptual model. It should be assumed that areas of LNAPL penetration would "pinch out" and that saturation values of LNAPL in the porous media would likewise decrease with distance from the source, and not truncate, as presented in prior discussions.

(3) Multiple Sources. Multiple sources have been cited to explain the presence of LNAPL in certain wells, although these specific wells have not been cited by name. A review of the soil data contained in the OU-3 RI (IT Corp, 1993), in comparison to LNAPL (free product) monitoring data seems to support a single continuous, if not homogeneous, LNAPL plume. If data is available to support the multiple release-multiple LNAPL plume approach it should be integrated into the site model.

Vertical Delineation

(4) Snapshot Calculation Approach. Consideration should be given to adding to the free product value a residual LNAPL value that might be present below the water table plus a residual LNAPL value in the unsaturated zone above the water table to reach a total value. The assumption that floating LNAPL equals all the LNAPL in the aquifer ignores LNAPL residual saturation in unsaturated zone above the floating LNAPL and ignores LNAPL residual saturation in saturated smear zone below the water table.

(5) Additional LNAPL above the Shallow Aquifer. Consideration should be given for LNAPL within the low permeability layer and LNAPL on top of the water table at 1150+ feet MSL (even if not measured).

(6) Disappearance of LNAPL During 1990-95. The disappearance of LNAPL in monitoring wells during the water table rise of 1990 through 1995 has been used to support the supposition that as the water table rose during the early 1990s there was not enough product present in the aquifer units to smear through the units and still allow LNAPL to appear in the wells. While the scenario described appears plausible, it does not seem consistent with the LNAPL thicknesses measured in the wells or the analysis presented above.

The most significant cases of LNAPL disappearance, in W-18 and LI-06, can be explained by screen submergence. Significant saturations of NAPL, i.e., mobile NAPL could be present yet physically unable to enter the submerged well screen. An additional explanation is based on the product removal activities.

(7) Lower Level of LNAPL Residual Saturation is 1120 feet MSL. This value seems to be too high of an elevation. This level appears to be based on the supposition that there is a lower permeability subunit from 1120 feet down to some elevation above the lowest water table elevation (1108 feet MSL), and that LNAPL could not have penetrated this subunit when the water level dropped to 1108 feet MSL. It is unclear if there is a low permeability unit of adequate thickness and permeability to have behaved in this manner. Data should be presented to support this assertion. In addition, it appears as though LNAPL has been measured in monitoring wells when the water level was in these lower levels.

(8) Upper level of LNAPL is equivalent to the top of aquifer which is equivalent to 1131

feet MSL. The aquifer has become confined, and while residual may extend beyond (above) this elevation, this elevation may be a useful level upon which to base a discussion for remediation of the Shallow Aquifer.

(9) LNAPL Migration. LNAPL clearly was able to migrate through the LPZ, a relatively impermeable fine-grained unit. This indicates that such migration was possible, although it could be due to preferential flow paths. It is possible that LNAPL could also migrate through the finer-grained units within the Shallow Aquifer. BEM's contention (BEM, 1999b) is that LNAPL migration did not occur because these units were saturated due to the short time period in which the water table elevation dropped below these units. There are two potential problems with this contention. First, LNAPL movement is possible through the preferential flow paths (cracks or areas of higher permeability that were unsaturated). Second, the short time period is apparently based on extrapolation of water table elevations and a correlation with the hydrograph for the deep aquifer well BP-06. The reliability of the extrapolated water table elevations is questionable. For example, BEM concludes (BEM 1998; 1999a) that the lowest water table elevations in the source area, interpolated using W-27 and W-29, was between 1110 and 1112 ft MSL. However, the available data points for BP-06 and LI-06 indicate an average 32 ft difference in water table elevations. A correlation and then extrapolation using these wells, would indicate that the lowest water table elevation in LI-06 (which is in the source area) would have been about 1105-1110 ft MSL. This could be significant in terms of the thickness of the LNAPL-affected units.

(10) Data Limitations. Water table elevation measurements at the time of LNAPL presence in wells indicate that LNAPL was present at least as deep as 1118 ft MSL. This is the deepest confirmed depth in most cases simply because there are no measurements for elevations (or times) before that elevation was reached.

LNAPL Saturation Values

(11) Residual Saturation Value. See discussion elsewhere in the detailed analysis of LNAPL volumes.

(12) Insignificant LNAPL Recovery Rates. It has been noted that if large volumes of mobile LNAPL were present below the site, then larger volumes of LNAPL would have been recovered to date. This observation/conclusion should be supported with a detailed analysis. The site record is unclear with respect to the efficiency of the recovery efforts and therefore, this issue remains unresolved. A detailed summary of NAPL recovery activities, design documents, and data (volume, and cost), etc., have not been provided. As such, an analysis and decision regarding NAPL mobility and recovery cannot be made.

More input on this general issue will be provided to you after a complete analysis of past LNAPL recovery efforts at Williams AFB and NAPL volume estimation have been reviewed. It is my understanding that a detailed summary of this activity is currently under preparation by the Air Force and will be submitted to EPA Region 9 with the Focused Feasibility Study. This is reflected by the following comment which was forwarded by you to the Air Force in October/November, 1998.

"It is recommended that this section be changed to "Pilot Studies/Treatability Studies and Detailed Cost Estimate". Costs should be calculated for each treatability study or remediation effort. For example, accurate documentation of the actual costs of NAPL recovery and a detailed description of the methods used to recover NAPL should be provided by the USAF. The purpose of the data and information would allow ADEQ and EPA to evaluate whether effective or cost efficient methods were used to recover NAPL, and whether it is economically practicable to recover the NAPL at Williams AFB. These issues must be evaluated. Such information, in conjunction with other data and information regarding natural attenuation should be used to determine whether NAPL recovery should be an integral component of the overall remedial approach used at WAFB."

(13) LNAPL Mobility Issue. It was proposed that the occurrence of a floating LNAPL layer in wells is that the "Free product overcame the capillary force and is slowly released from pore space to adjacent well"(BEM Tech Memo, 6/10/98, "Attachment F", p. 4).

The basis for this statement is unclear. Previously, it has been communicated that the NAPL contained in the aquifer at this location was at residual saturation. The effective definition for residual saturation is that the NAPL is immobile. Based on this definition, it is unclear how immobile NAPL can become significantly mobile to the point that it collects in a well is the thicknesses measured at these locations. Therefore, the proposed explanation of NAPL mobility seem implausible, i.e. it does not address how the capillary forces were overcome.

Alternatively, one possible scenario is that the NAPL saturation is much greater than the presumed residual saturation. For example, the floating product signifies mobile LNAPL (i.e., LNAPL above residual saturation).

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ATTACHMENT 1 - BTEX Phase Distribution

The mass of contaminants (BTEX) in each phase were estimated. This was based on the following parameter values, total volume 1 m^3, $\eta = 0.35$, $\rho_B = 1.6$ g/cm^3, volumetric NAPL saturation = 0.17, NAPL density = 0.85 g/cm^3,

	K_{OC}	Effective Solubility (mg/L)	f_{OC}	Mass fraction
benzene	65	42	0.1	0.005
toluene		257 27		0.1 0.013
ethyl benzene	676	2	0.1	0.0037
xylenes	691	16	0.1	0.0232

In the mass distribution analysis it was assumed that the BTEX was in the aqueous phase, sorbed phase, and NAPL phase. Mass distribution of BTEX in NAPL, water, and soil was calculated to be 894, 0.29, and 3.6 (moles), respectively. These values correspond to a mole fraction of 0.9957, 0.0003, and 0.004 for the NAPL, water and solid phases, respectively. These data indicate that these constituents were primarily present in the NAPL phase. Therefore, the primary focus of the contaminant mass estimate was based on the NAPL phase only.